ECOLOGICALLY-BASED LIFE CYCLE ASSESSMENT OF CORN STOVER BIOFUELS

UNDERGRADUATE HONORS RESEARCH THESIS

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Abstract

Cellulosic biofuels are becoming a popular option for alternative fuels that could decrease fossil fuel consumption and greenhouse gas emissions without interfering with the food supply. At this point in time, studies of cellulosic fuels from a life cycle point of view have been largely limited to ethanol. Furthermore, most methods of life cycle assessment do not consider ecological goods and services, even though these are important precursors to any industrial project.

In this project, butanol, ethanol, and biodiesel fuels were compared using Eco-LCA. Fossil fuel requirements, water requirements, CO_2 emissions, reactive nitrogen losses to the environment, and Ecological Cumulative Exergy Consumption were quantified for the life cycle of each fuel. Gasoline, diesel, corn ethanol, and soybean biodiesel were included for purpose of comparison. The corn-stover-derived fuels were demonstrated to have numerous advantages, including lower fossil fuel requirements and ECEC than their petroleum based counterparts, while also having lower water requirements and reactive nitrogen losses than corn ethanol and soybean biodiesel.

Acknowledgments

I would like to thank Dr. Bhavik Bakshi for providing me with the opportunity to work on this project and offering guidance as the project developed, Erin Landers for helping and encouraging me throughout the duration of this project, Shweta Singh for assisting me as I sought to learn the basics of life cycle assessment, and Dr. Shang-Tian Yang for helping me to better understand the processes by which biofuels are made.

Table of Contents

Abstract . . . . **ii**

Acknowledgments . . . . **iii**

List of Figures . . . . **vi**

List of Tables . . . . **vii**

1 Introduction **1**

2 Background **3**

2.1 Ethanol 3

2.2 Butanol 5

2.3 Biodiesel 5

3 Objective **6**

4 Methods **6**

4.1 Eco-LCA 6

4.2 Data Sources and Assumptions 7

4.3 Resource Allocation 8

4.4 Data Organization 9

5 Results **10**

5.1 Resource Intensity: Fossil Fuels and Water 10

5.2 Carbon and Nitrogen 13
5.3 Ecological Cumulative Exergy Consumption 22

6 Comparison with Previous Studies 25

7 Conclusions 26

References 28

Appendix A Fuel and Feedstock Properties and Assumptions 33

Appendix B Inputs for Fuel Production Processes 34

Appendix C Results Tables 38

Appendix D Calculations 41

List of Figures

1 Fossil Fuel Requirements for Gasoline, Ethanol, and Butanol 10

2 Fossil Fuel Requirements for Diesel and Biodiesel 11

3 Water Requirements for Gasoline, Ethanol, and Butanol 12

4 Water Requirements for Diesel and Biodiesel 13

5 CO_2 Sequestration and Emissions in Fuel Production 14

6 Well-to-tank Net CO_2 Emissions 15

7 Well-to-Wheel CO_2 Emissions for Gasoline, Ethanol, and Butanol . . 16

8 Well-to-Wheel CO_2 Emissions for Diesel and Biodiesel 17

9 Nitrogen Mobilization for Gasoline, Ethanol, and Butanol Production 18

10 Nitrogen Mobilization for Diesel and Biodiesel Production 19

11 Well-to-Tank Reactive Nitrogen Losses 20

12 Nitrogen Losses During Gasoline, Ethanol, and Butanol Production . 21

13 Nitrogen Losses During Diesel and Biodiesel Production 22

14 ECEC for Fuels on an Energy Equivalent Basis 23

15 ECEC for Gasoline, Ethanol, and Butanol Production 24

16 ECEC for Diesel and Biodiesel Production 24

List of Tables

1 Dry Mass of Corn Stover Required to Produce 514 billion Btu of Fuel 33

2 Densities and Lower Heating Values of Fuels 33

3 Fuel Economy and CO_2 Emissions for Different Fuels 33

4 Inputs for Producing Corn Stover Ethanol via Fermentation 34

5 Inputs for Producing Corn Stover Ethanol via Gasification 35

6 Inputs for Producing Corn Stover Butanol 36

7 Inputs for Producing Corn Stover Biodiesel 37

8 Fossil Fuel Use, Water Use, and CO_2 Emissions for 514 billion Btu of Fuel 38

9 Fossil Fuel Use, Water Use, and CO_2 Emissions for 1 km in a 2012 Ford Fusion 38

10 Fossil Fuel Use, Water Use, and CO_2 Emissions for 1 km in a 2012 Volkswagon Jetta 39

11 Nitrogen Footprint for 514 billion Btu of Fuel 39

12 Nitrogen Footprint for 1 km in a 2012 Ford Fusion 39

13 Nitrogen Footprint for 1 km in a 2012 Volkswagon Jetta 40

14 Total ECEC for 514 billion Btu of Fuel 40

15 Total ECEC for 1 km in a 2012 Ford Fusion 40

16 Total ECEC for 1 km in a 2012 Volkswagon Jetta 40

1 Introduction

At a time when concerns about global warming, pollution, and sustainability are becoming increasingly widespread, many people are looking for ways to decrease the toll human activities place on the environment. This is demonstrated by government subsidies that encourage the production and use of alternative energy sources and also by the large quantity of advertising for “flex-fuel” vehicles and other “green” products. One result of this growing concern has been increased research in the area of alternative fuel technologies. Implementation of such technologies has become a requirement–the Environmental Protection Agency (EPA) has developed many policies and regulations that are intended to increase sustainability among industrial practices. For example, in March of 2010, the EPA published revisions to the Renewable Fuel Standard Program that included required volumetric production rates of cellulosic biofuels, biomass-based diesel, advanced biofuels, and total renewable fuels for each year through 2022. [1]

Traditional methods of producing biofuels require crops such as corn and soybeans as a feedstock. Many are concerned with the idea of devoting these crops to transportation and other fuels because they are also widely used in the food industry for feeding both people and animals. They believe that introducing another industry that utilizes these resources will increase food costs. To further the development of biofuels amidst these concerns, cellulosic biofuels produced from currently unused materials, such as agricultural residue, are gaining popularity. Furthermore, previous studies suggest that ethanol produced from cellulosic feedstocks could reduce greenhouse gas emissions and fossil fuel requirements even more than the current corn grain technology. [2, 3] One cellulosic feedstock, corn stover, is the agricultural residue that often remains in the cornfield after harvest. Corn stover consists of 65% cellulose and hemicellulose and is one possible feedstock for the production of cellulosic biofuels. [4] Many researchers view corn stover as a promising feedstock for biofuels because it is readily available and does not impact the food supply. Studies have also shown that the use of corn stover instead of corn grain for ethanol production further decreases fossil fuel energy requirements. [5] The main concern regarding the use of corn stover and other types of agricultural residue in industry is the effect that the removal of this material may have on the soil. However, researchers have demonstrated that partial removal of corn stover can be practiced in many areas without causing significant soil erosion. [6, 7]

Discussions about alternative fuels often focus on the emissions released during fuel combustion and the idea of "carbon neutral" fuels–fuels that release carbon compounds that were recently removed from the atmosphere. However, the carbon released during fuel combustion is not the only carbon emitted during the fuel's life cycle, and there are also many factors other than carbon emissions that must be considered. Life Cycle Assessment (LCA) is one method of looking at the broad-scale environmental implications of industrial activity.

LCA considers the effects of all stages of a product's life cycle, from the initial pre-production stages to end-use. This allows researchers to determine whether one product or process is truly more sustainable than another. LCA is becoming increasingly popular as scientists are realizing that ignoring certain parts of the life cycle often merely causes the brunt of the environmental impact to shift to something else. [8] The Environmental Protection Agency is currently using LCA in order to consider greenhouse gas emissions of fuels. Such assessments were used in the development of the 2010 revision to the Renewable Fuel Standard Program. [1]

However, most current methods of LCA are based solely on economic activity and do not incorporate ecosystem goods and services into the analysis, even though industries heavily rely on these services. [9] All of the raw materials for industrial processes are produced by ecosystems. Without considering this aspect, the overall environmental impact of human activities cannot be determined. The method of Ecologically-Based Life Cycle Assessment (Eco-LCA) that will be used extensively in this project accounts for these ecosystem services and therefore will provide a more complete picture of the environmental impact of a product's life cycle. [9]

This work focuses on using Eco-LCA to evaluate ethanol, butanol, and biodiesel made from corn stover. Ethanol and biodiesel are both currently available biofuels, but making these fuels from a feedstock such as corn stover could provide additional advantages. Butanol is considered a promising option because it has a much higher energy density than ethanol and 100% butanol can be used in gasoline vehicles without modification. [10]

2 Background

2.1 Ethanol

The majority of studies investigating the production of biofuels from corn stover, especially from a LCA perspective, have focused on ethanol. Corn ethanol has been widely promoted in recent years, with more than 8.3 million E85 flex-fuel vehicles on the road in the United States since the end of 2009 [11] and 10% ethanol gasoline blends replacing 100% gasoline at many gas stations across the nation. While corn grain is currently the main feedstock for commercial ethanol production, processes for producing ethanol from corn stover and other cellulosic feedstocks have been developed, modeled, and analyzed using LCA. These studies have shown that ethanol produced from corn stover has much lower process energy input requirements than ethanol produced from corn grain, with a 74% decrease reported by Swana et al. [10]

The most common method of producing ethanol (and therefore the most studied mechanism) involves the fermentation of sugars. [2] Baral et al. [12] completed a study that analyzed resource use for the production of cellulosic ethanol from several feedstocks, including corn stover, and showed that cellulosic ethanol had 88-96% reductions in life cycle crude oil consumption as compared to gasoline but required 2-3 times as much natural gas. Similar results from a study by Sheehan et al. [3] showed that ethanol from corn stover could decrease crude oil requirements by 95%, and Levelton Engineering Ltd. [13] found a 74% reduction in overall fossil fuel consumption. Spatari et al. [14] found a 71% reduction in CO_2 life cycle emissions when an E85 blend of cellulosic ethanol made from corn stover was compared to reformulated gasoline. Numerous other studies have also described decreases in greenhouse gas emissions that would result from replacing gasoline with cellulosic ethanol, but the reported reductions vary considerably from study to study.

Other mechanisms, such as gasification and pyrolysis, have also been investigated and compared to the traditional fermentation mechanism. These studies have demonstrated that fermentation and gasification methods of producing cellulosic ethanol have similar production rates and efficiencies within the plant, [2] and therefore studying both processes and comparing them from a life cycle point of view is worthwhile. However, most studies have only focused on the direct emissions from the production plants and not on the inputs required for ethanol production via gasification or pyrolysis. [2] Mu et al. [2] did compare these two processes using LCA, however, and they showed that the thermochemical process requires a much lower water consumption than the biochemical process. In their study, the allocation method used to divide resources between the ethanol and electricity produced by the biochemical production process had a great effect on which process had lower fossil fuel requirements. [2]

2.2 Butanol

Processes for producing butanol from cellulosic biomass were developed as early as 1980. [15] However, biobutanol has not been largely considered as an option for transportation fuel until much more recently. Today, many scientists consider butanol as a promising option for a new transportation fuel because its energy content (as measured by the Lower Heating Value) is 30% higher than that of ethanol. [16] However, nearly all of the studies comparing ethanol and butanol, especially in terms of LCA, have used corn grain rather than a cellulosic feedstock. In one of these studies, researchers demonstrated that the allocation method used affected whether corn butanol or corn ethanol was more favorable in terms of both fossil fuel consumption and greenhouse gas emissions. [16] While LCA results for butanol production from cellulosic materials are not readily available, the substantial reductions in fossil fuel consumption for cellulosic ethanol compared with corn ethanol suggest that cellulosic butanol could also have many advantages over corn butanol. Furthermore, the possibility of using 100% butanol as a transportation fuel rather than gasoline blends offers another advantage.

2.3 Biodiesel

Biodiesel has been produced from oil-containing feedstocks such as soybeans for some time, but there have been few studies using cellulosic feedstocks for this fuel. However, researchers are now suggesting that diesel fuel can be produced from feedstocks such as corn stover and wood chips by using one of two processes that have already been used to produce diesel fuel from coal: gasification followed by a Fischer-Tropsch reaction or pyrolysis followed by hydrocracking. Many researchers have studied gasification and pyrolysis processes for wood-based feedstocks, but only a few assessments of the conversion processes used to produce diesel fuel from the resulting pyrolysis oils are available. In one study completed by Ahlgren et al. [17], it was demonstrated that Fischer-Tropsch diesel made from straw could reduce greenhouse gas emissions by as much as 94% as compared to conventional diesel fuel.

3 Objective

The purpose of this project was to investigate the environmental advantages and disadvantages of using corn stover to produce biodiesel, bioethanol, and biobutanol. Each of these fuels, as well as gasoline, diesel, corn ethanol, and soybean biodiesel, was studied using Eco-LCA. Carbon and nitrogen footprints, water use, fossil fuel energy consumption, and Ecological Cumulative Exergy Consumption were determined in order to evaluate and compare each fuel. Comparisons were made for each fuel on an energy content basis. Blends used in transportation fuels were also used to compare the fuels on a per km basis by comparing the use of gasoline, ethanol, and butanol in a vehicle with a flex-fuel engine and comparing diesel and biodiesel in a car with a diesel engine.

4 Methods

4.1 Eco-LCA

Resource consumption and emissions for each of the fuels studied were estimated using Eco-LCA with the material and energy inputs to the industrial fuel production processes. Like many economic input-output models, Eco-LCA uses economic sectors in an input-output model, but it also considers numerous ecological goods and services that support these economic activities. Eco-LCA relates resource intensities to economic costs, so prices of each of the process inputs are used to quantify the activity within each sector and to obtain results.

4.2 Data Sources and Assumptions

Three fuels made from corn stover were studied: ethanol, butanol, and biodiesel. Two different production processes were considered for corn stover ethanol production: the traditional biochemical process consisting of hydrolysis and fermentation and a thermochemical process involving indirect gasification followed by Fischer-Tropsch synthesis. Gasoline, diesel, corn ethanol, and soybean biodiesel were also included in this study in order to compare each of the corn stover fuels with the fuels they could potentially replace.

The biochemical process for producing cellulosic ethanol consists of a dilute acid prehydrolysis step followed by simultaneous enzymatic saccharification and fermentation. [18] The thermochemical process used in this study is an indirect gasification process followed by Fischer-Tropsch synthesis. [19] The indirect gasification using olivine for heat exchange was chosen because this option was shown to be more economical than direct gasification. [20] Process data were obtained from the model used by Phillips et al. [19] for ethanol production from wood chips and from a report by Mu et al. [2] that adjusted this process for additional feedstocks based on their cellulose and hemicellulose contents. Quantities of chemicals required for wastewater treatment, cooling water, and boiling water were estimated based on the amounts required for the biochemical ethanol production process, scaling them by the total amount of water required.

For the butanol production process, the pretreatment steps (such as hydrolysis) were equivalent to those used in the biochemical production of ethanol, and inputs per kg of corn stover for that process were used. Butanol fermentation yield was estimated using relative laboratory scale yields for ethanol and ABE. [21, 10] Energy requirements for the fermentation of acetone, butanol, and ethanol (ABE) and the distillation of butanol from the mixture were taken from a simulation performed by Wu et al. [16] This process modeled the production of butanol from corn grain rather than corn stover, but experiments studying the fermentation of corn stover hydrolysates have used the same strain of yeast, Clostridium beijerinckii, with identical reaction conditions. [22, 23] It was also shown that this strain can give the same ABE yield for glucose and xylose, [23] the products of cellulose and hemicellulose hydrolysis, suggesting that it is reasonable to assume that the energy requirements for the ABE fermentation step are equal for corn grain and corn stover feedstocks.

The corn stover biodiesel process studied in this report used fast pyrolysis to produce a bio-oil and then hydroprocessing to yield biodiesel. [24] The pyrolysis bio-oil could be used to produce the hydrogen necessary for upgrading to biodiesel, but this study will focus on the scenario where hydrogen is purchased rather than produced. The main reasons for this decision were that the high cost of the hydrogen production technology deems the use of this technology in pioneer plants infeasible until this technology is further developed and that using a hydrogen purchase scenario allows 64% more diesel fuel to be produced from the same amount of corn stover. [24]

For all of the corn stover-based fuels, the farm inputs for corn stover collection (diesel fuel for the tractor and fertilizer to replace the minerals removed with the corn stover) were taken from the study completed by Spatari et al. [14] Concrete and steel requirements for the biochemical ethanol production plant were based off of a report by Felix, [25] and estimates of the total installed equipment cost and fuel production capacity for each production plant were used to scale these values for the other plants.

4.3 Resource Allocation

For allocation of farming inputs, it was assumed that corn stover was considered an agricultural waste. Therefore, inputs such as pesticides, herbicides, and grain seed were not included as these were allocated to the corn grain instead. Resources were allocated to the products of the fuel production processes on an energy basis. For the biochemical ethanol production process, 91.6% of the energy output was in the form of ethanol. [18] This value was 91.3% for butanol because more of the electricity generated by lignin combustion was used during the production process. [10] The remainder of the energy output was electricity for both of these processes. The process for butanol production produced acetone and ethanol in addition to the butanol, and the thermochemical ethanol production process also produced higher alcohols, but this study did not include the energy necessary to separate and purify these compounds and therefore they were not treated as useful fuel output. This extra energy requirement was not included because other studies have shown that purifying butanol only provides a much higher net energy return. [10] For the biodiesel production, naphtha-grade fuel was a significant portion of the fuel output, and therefore only 53.1% of the resources were allocated to biodiesel. [24]

4.4 Data Organization

In order to compare each of the fuels studied, net carbon dioxide emissions, nitrogen mobilization, reactive nitrogen losses to the environment, fossil fuel requirements, water requirements, and Ecological Cumulative Exergy Consumption were calculated for the life cycle of each fuel. All of the fuels in their pure form were compared on an energy equivalent basis. In order to better compare the resource requirements and emissions related to fueling a car, each of the fuels were also compared on a per km basis. Gasoline, 100% butanol, 10% ethanol/90% gasoline, and 85% ethanol/15% gasoline were compared assuming a 2012 Ford Fusion flex-fuel vehicle. Diesel, 20% biodiesel, and 100% biodiesel were compared assuming a 2012 Volkswagon Jetta with a diesel engine.

5 Results

5.1 Resource Intensity: Fossil Fuels and Water

Decreasing dependence on fossil fuels is seen as one of the main advantages of biofuels. Figure 1 shows the fossil fuel consumption per km for driving a 2012 Ford Fusion powered by gasoline, butanol, and common ethanol blends of E10 and E85 for each of the ethanol production methods. As shown in the figure, corn stover butanol, corn stover E85 produced via fermentation, and corn stover E85 produced via gasification decrease crude oil consumption by 98%, 71%, and 78%, respectively. Over all fossil fuel requirements are 83% lower than gasoline for corn stover butanol, 59% lower for corn stover ethanol produced via fermentation, and 67% lower for corn stover ethanol produced via gasification.

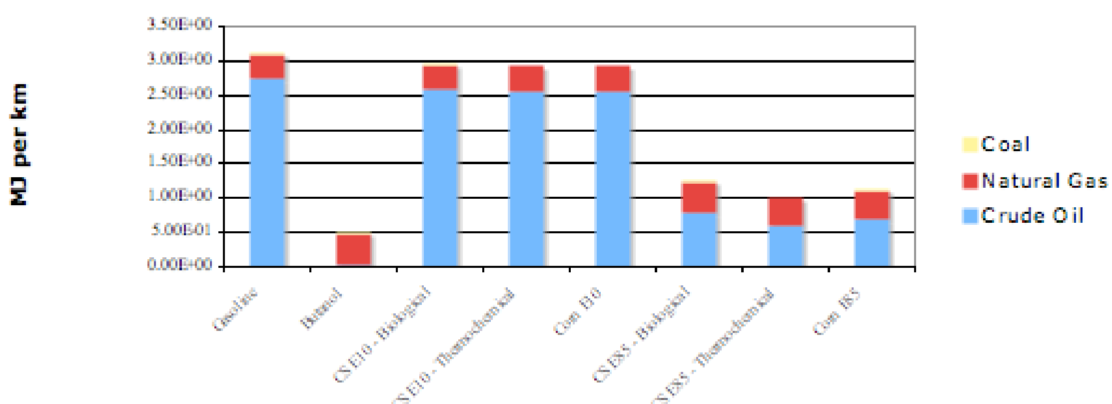

Figure 1: Fossil fuel requirements for gasoline, 100% butanol, 10% ethanol/90% gasoline, and 85% ethanol/15% gasoline. Resource requirements are for driving 1 km in a 2012 Ford Fusion flex-fuel vehicle.

Figure 2 makes the same comparison with diesel, B20, and B100, where the biodiesel in each blend is made from either corn stover or soybeans. B100 gave a crude oil consumption reduction of 99% compared to diesel when made from corn stover and 95% when made from soybeans. The natural gas requirement for producing corn stover biodiesel was 66% higher than for diesel due to the hydrogen requirement. This gives an overall fossil fuel reduction of 80% for biodiesel made from corn stover and 86% for biodiesel made from soybeans.

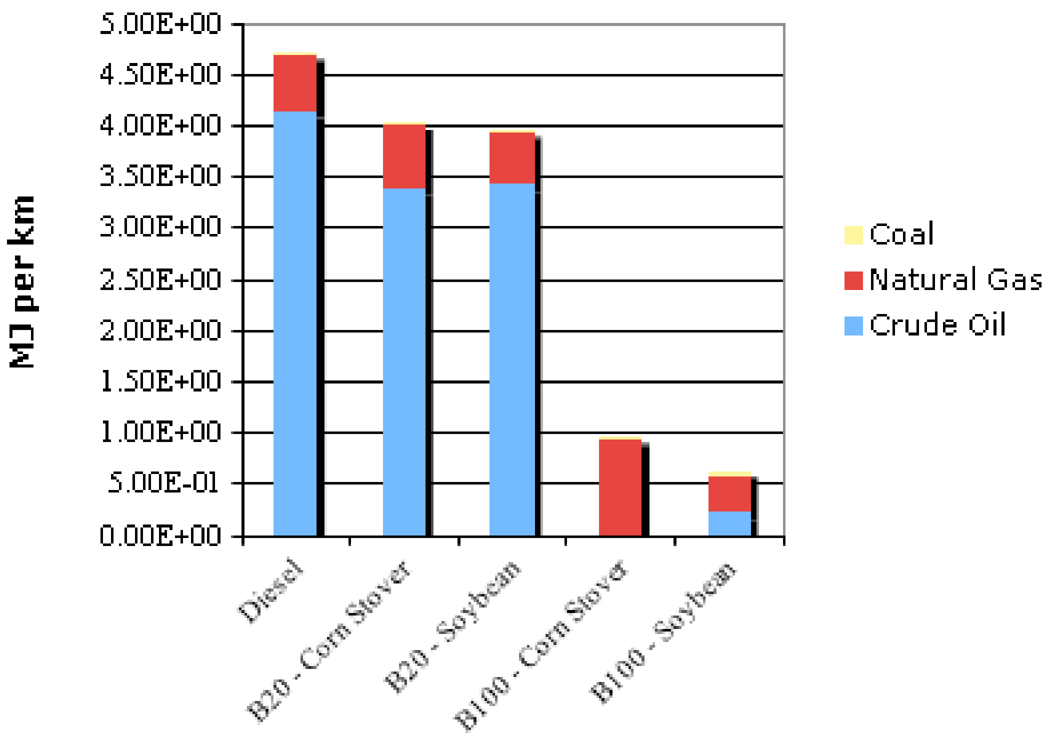

Figure 2: Fossil fuel requirements for diesel, 20% biodiesel/80% diesel, and 100% biodiesel. Resource requirements are for driving 1 km in a 2012 Volkswagon Jetta diesel powered vehicle.

Water requirements for the two sets of fuels are shown in Figures 3 and 4. As shown in Figure 3, all of the biofuels have higher water requirements than gasoline except for the gasification mechanism for cellulosic ethanol production. E85 using corn ethanol requires more than 10 times as much water as gasoline due to the water necessary for farming. Butanol and E85 from fermentation of corn stover hydrolysates require between 2 and 2.5 times as much water as gasoline. This same trend is shown for the diesel fuels in Figure 4–corn stover biodiesel requires approximately 1.5 times as much water as diesel while soybean biodiesel requires more than 11.5 times as much water.

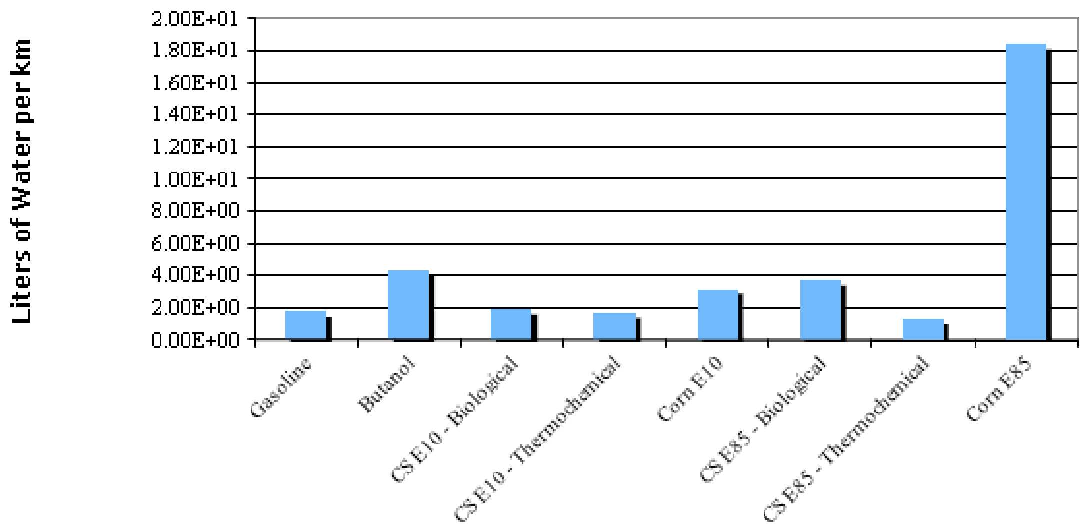

Figure 3: Water requirements for gasoline, 100% butanol, 10% ethanol/90% gasoline, and 85% ethanol/15% gasoline. Resource requirements are for driving 1 km in a 2012 Ford Fusion flex-fuel vehicle.

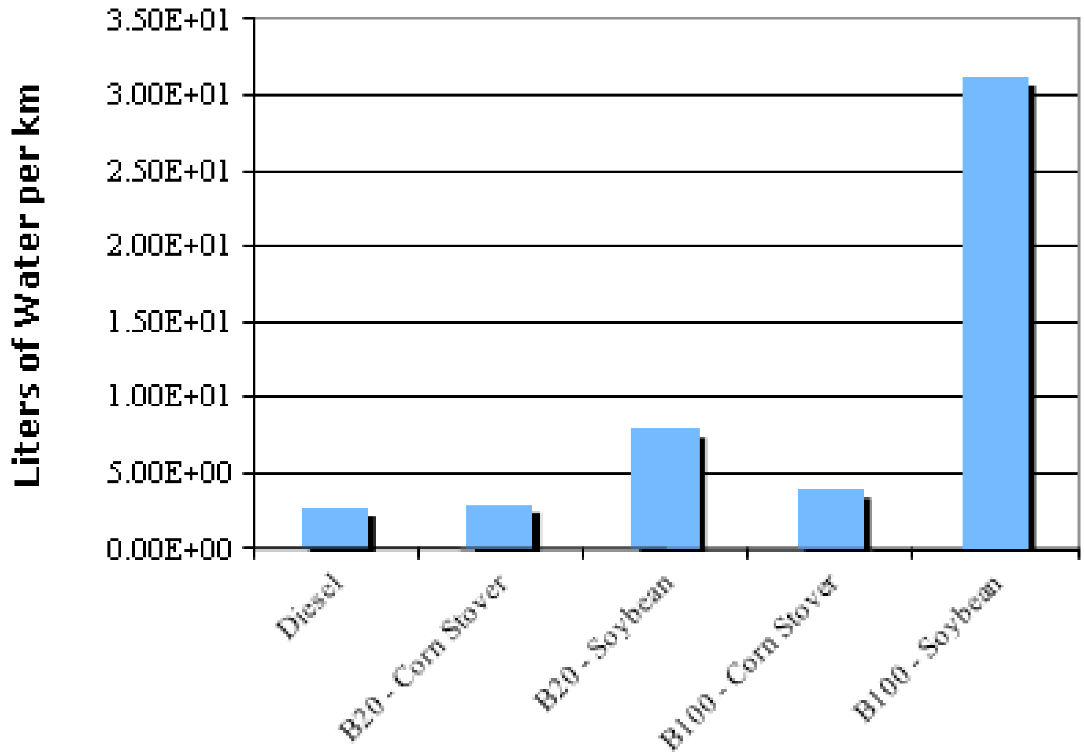

Figure 4: Water requirements for diesel, 20% biodiesel/80% diesel, and 100% biodiesel. Resource requirements are for driving 1 km in a 2012 Volkswagon Jetta diesel-powered vehicle.

5.2 Carbon and Nitrogen

Reducing carbon emissions is another one of the main reasons why scientists and policymakers are looking to alternative fuels. CO_2 emitted and sequestered for all of the steps leading up to fuel use is shown in Figure 5, and the net CO_2 emissions for this portion of the life cycle are shown in Figure 6. Carbon sequestration related to corn ethanol production is almost 17 times as high as for gasoline, and carbon sequestration for soybean biodiesel is more than 22 times as high as for diesel. While carbon sequestered during farming cannot be considered an advantage for the corn stover biofuels because they were considered an agricultural waste, the well-to-tank emissions are much lower, giving net CO_2 emission reductions of 64-59% for corn stover ethanol over gasoline and 13% for corn stover biodiesel over petroleum diesel. The lower reduction for the corn stover biodiesel is due to the need for hydrogen production.

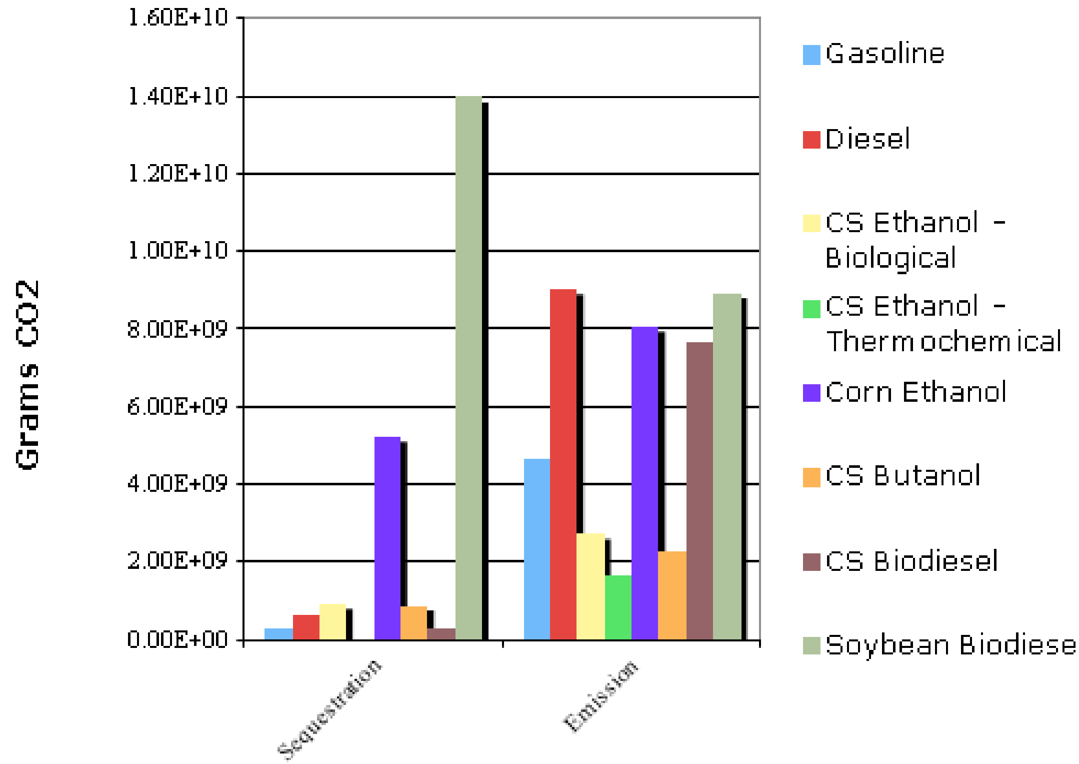

Figure 5: CO_2 sequestration and emissions during the production of 514 billion Btu of fuel.

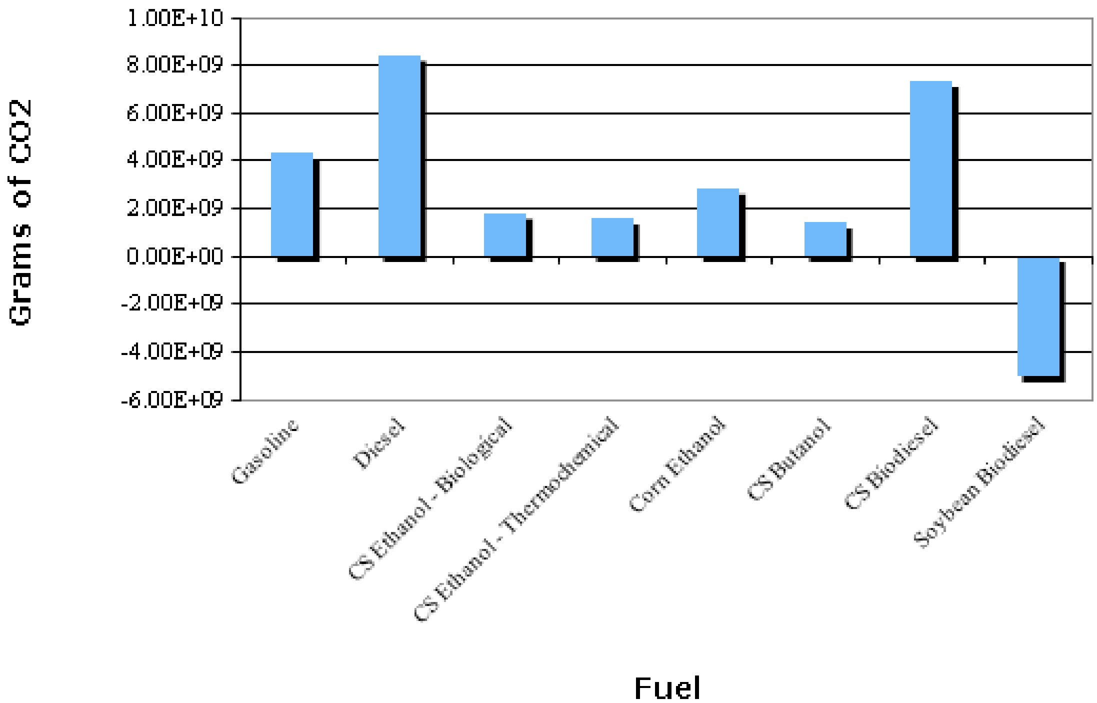

Figure 6: Well-to-Tank net CO_2 emissions for the production of 514 billion Btu of fuel.

While the well-to-tank carbon footprint is much lower for most of the biofuels, it is interesting to note that the majority of the carbon emissions are in the end-use combustion of the fuel. This is shown in the well-to-wheel carbon emissions of each fuel, as seen in Figure 7 for gasoline, butanol, and ethanol and Figure 8 for diesel and biodiesel. CO_2 emissions during fuel combustion account for approximately 90% of the life cycle CO_2 emissions for the fuel, and these tailpipe emissions are only 2-5% lower for biofuels than for their petroleum counterparts. Because of these, the overall CO_2 emissions for corn stover butanol are only 11% lower than for gasoline, emissions for corn stover ethanol are 6-7% lower than for gasoline, and emissions for corn stover biodiesel are 4% lower than for diesel. Only soybean biodiesel shows a larger decrease due to the higher carbon sequestration during soybean farming.

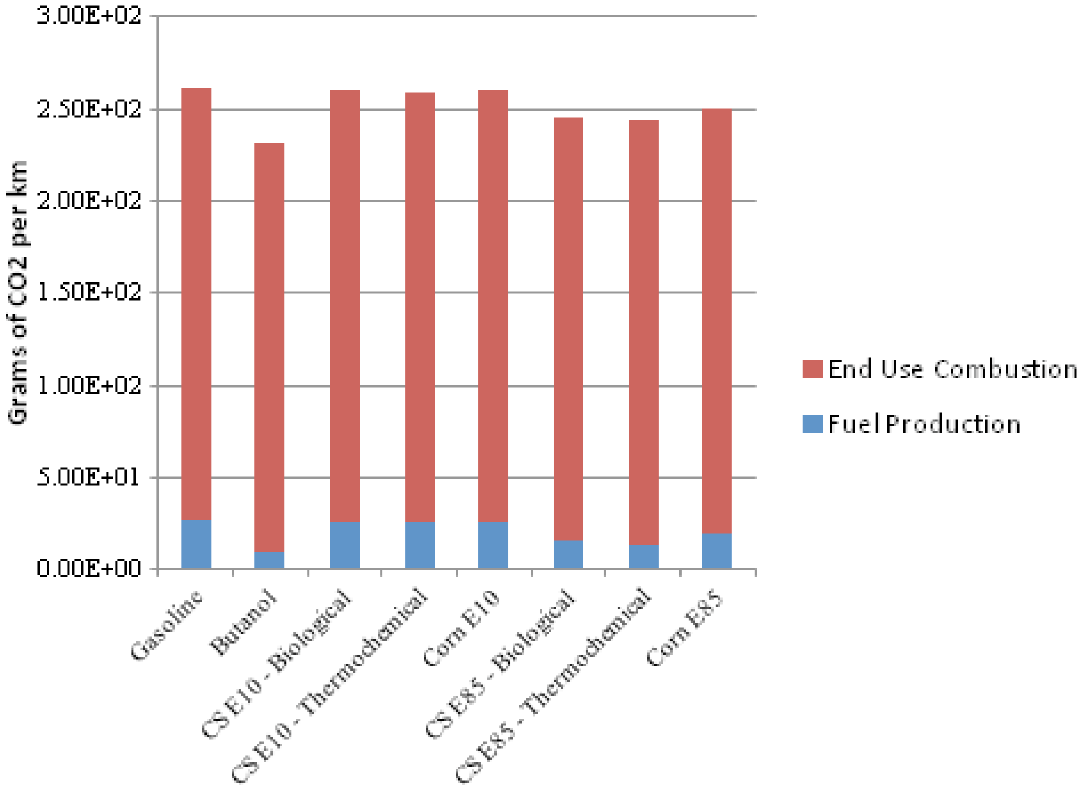

Figure 7: Well-to-wheel CO_2 emissions for gasoline, 100% butanol, 10% ethanol/90% gasoline, and 85% ethanol/15% gasoline. Emissions are for driving 1 km in a 2012 Ford Fusion flex-fuel vehicle.

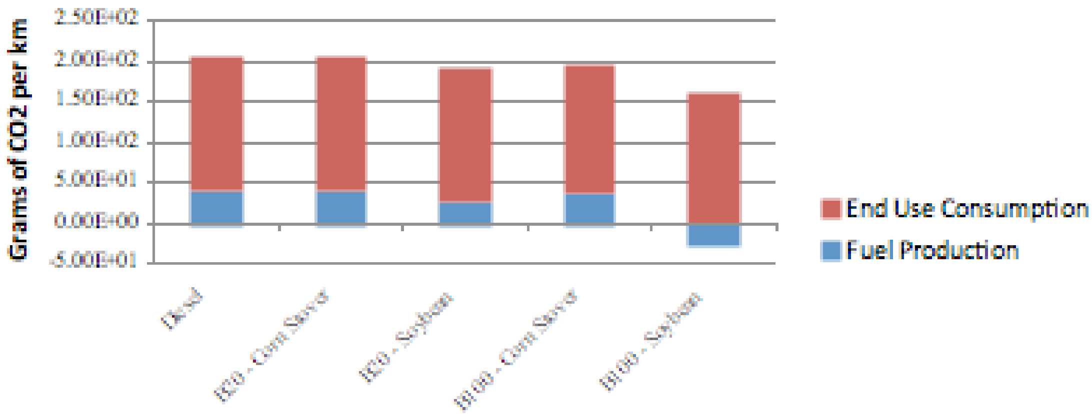

Figure 8: Well-to-wheel CO_2 emissions for diesel, 20% biodiesel/80% diesel, and 100% biodiesel. Emissions are for driving 1 km in a 2012 Volkswagon Jetta diesel powered vehicle.

The nitrogen footprint for each of the fuels was determined in terms of nitrogen mobilization and reactive nitrogen losses to the environment. Nitrogen mobilization for the two groups of fuels is shown in Figures 9 and 10. While nitrogen mobilization is very low for gasoline and diesel, it is quite high for all of the biofuels due to fertilizer requirements. In Figure 9, butanol has the highest value for nitrogen mobilization because it is 100% butanol rather than a blend with gasoline and therefore significantly more corn stover is required. Figure 10 shows a significant increase in nitrogen mobilization for soybean biodiesel over corn stover biodiesel, which is also due to increased farming and fertilizer requirements.

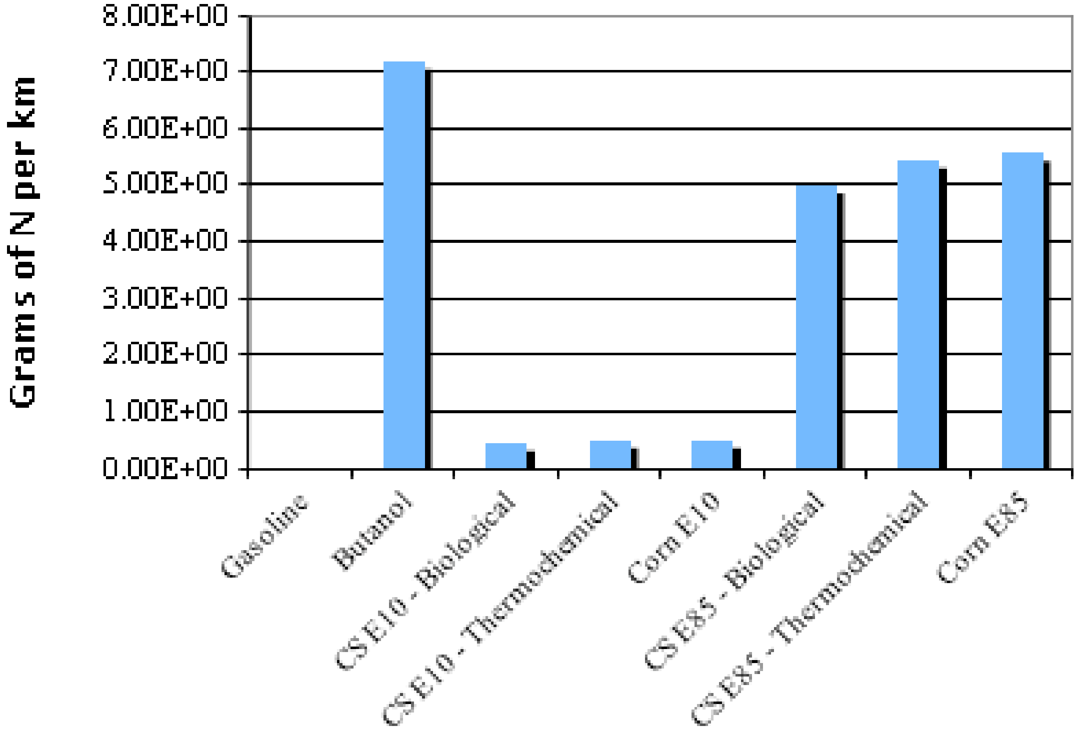

Figure 9: Nitrogen mobilization during the production of gasoline, 100% butanol, 10% ethanol/90% gasoline, and 85% ethanol/15% gasoline. Mobilized quantities are for driving 1 km in a 2012 Ford Fusion flex-fuel vehicle.

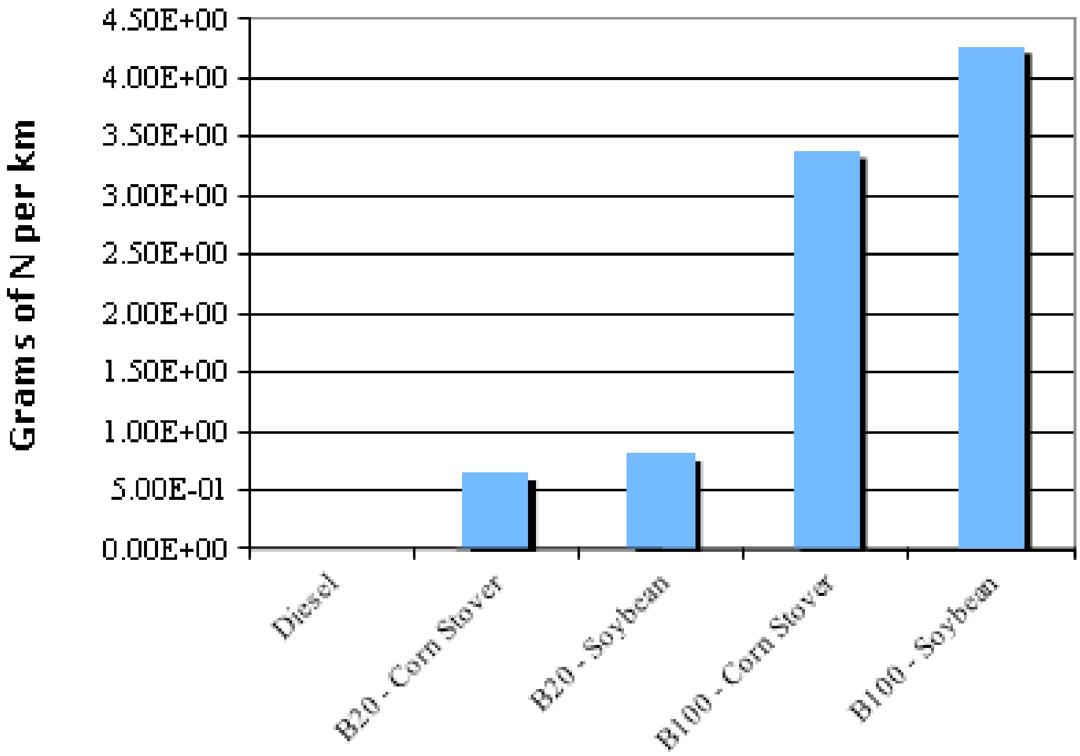

Figure 10: Nitrogen mobilization during the production of diesel, 20% biodiesel/80% diesel, and 100% biodiesel. Mobilized values are for driving 1 km in a 2012 Volkswagon Jetta diesel powered vehicle.

Reactive nitrogen lost to the environment was also determined for each of the fuel production processes. Nitrogen losses for the production of 514 billion Btu of each fuel are shown in Figure 11. Unlike nitrogen mobilization, reactive nitrogen losses are nearly equal for gasoline and for corn stover based fuels, but more emissions from the cellulosic fuels are in the form of N_2O while gasoline and diesel emissions are mostly NOx. Corn ethanol and soybean biodiesel have higher reactive nitrogen losses due to farming.

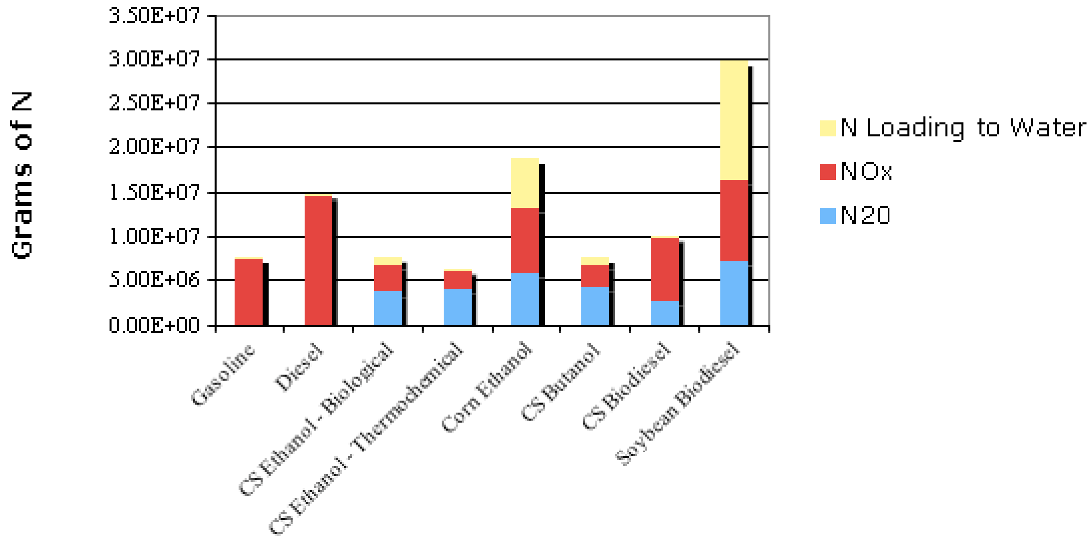

Figure 11: Reactive nitrogen losses to the environment during upstream and production processes. Losses are for 514 billion Btu of fuel.

The reactive nitrogen losses are shown on a per km basis in Figures 12 and 13. Nitrogen losses for butanol and E85 produced via fermentation are slightly higher than for gasoline while nitrogen losses for E85 produced via gasification are slightly lower. Nitrogen losses for biodiesel from corn stover are lower than those for diesel and for soybean biodiesel.

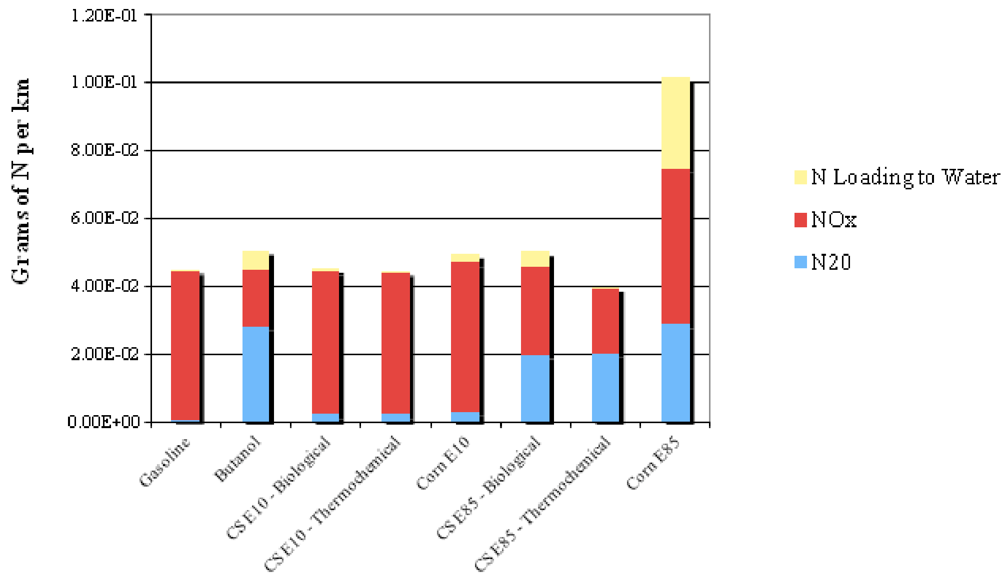

Figure 12: Reactive nitrogen losses related to the production of gasoline, 100% butanol, 10% ethanol/90% gasoline, and 85% ethanol/15% gasoline. Losses are for driving 1 km in a 2012 Ford Fusion flex-fuel vehicle.

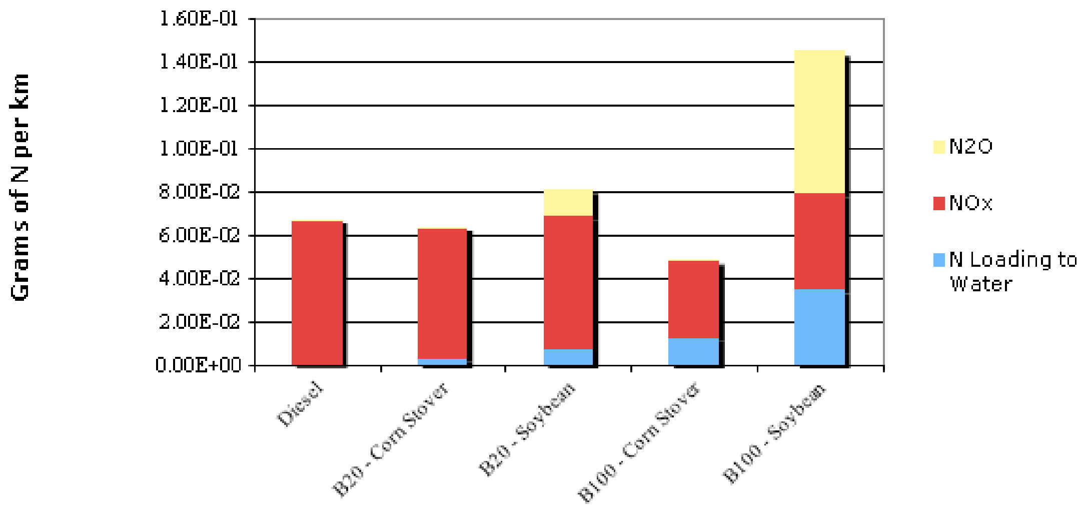

Figure 13: Reactive nitrogen losses related to the production of diesel, 20% biodiesel/80% diesel, and 100% biodiesel. Losses are for driving 1 km in a 2012 Volkswagon Jetta diesel powered vehicle.

5.3 Ecological Cumulative Exergy Consumption

Ecological Cumulative Exergy Consumption (ECEC) was used as a metric to compare the total amount of useful energy required to make each product. ECEC accounts for the exergy of each resource and ecological service required and combines all of these values by transforming them to solar equivalent joules. An ECEC comparison for all of the fuels is shown in Figure 14. ECEC for butanol and ethanol produced via fermentation are 65% and 59% lower than for gasoline, respectively. Higher ECEC is observed for the thermochemical production of cellulosic ethanol due to the material requirements for the bed of the reactor, but this value is still 39% lower than for gasoline. Corn stover biodiesel had the highest ECEC of all of the biofuels due to the mineral and natural gas requirements for hydrogen production, but even this value is 28% lower than for diesel fuel.

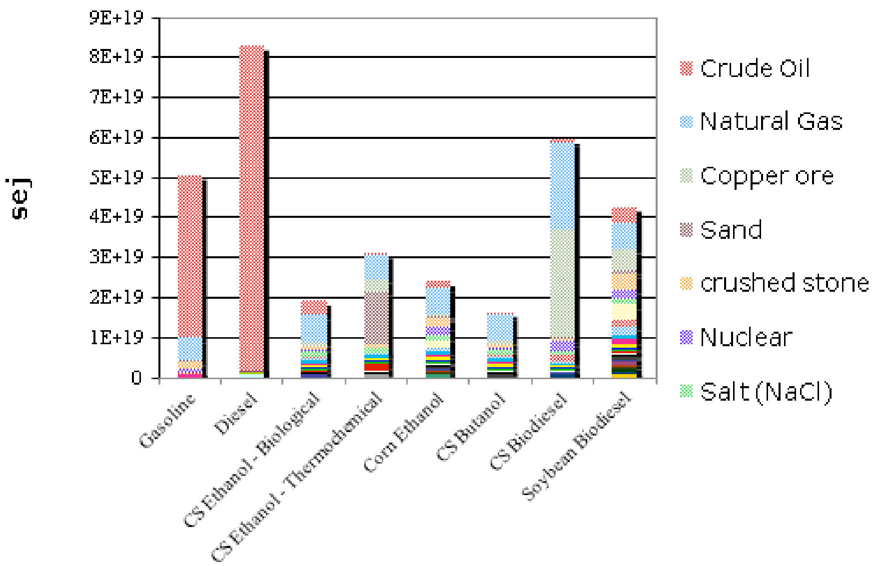

Figure 14: Ecological Cumulative Exergy Consumption for producing 514 billion Btu of fuel.

These trends are also shown by the per km ECEC for each fuel in Figures 15 and 16. In Figure 15, the fuels containing the least amount of gasoline have the lowest ECEC. In Figure 16, ECEC decreases with diesel fuel content and ECEC is lower for soybean biodiesel than for corn stover biodiesel, as described before.

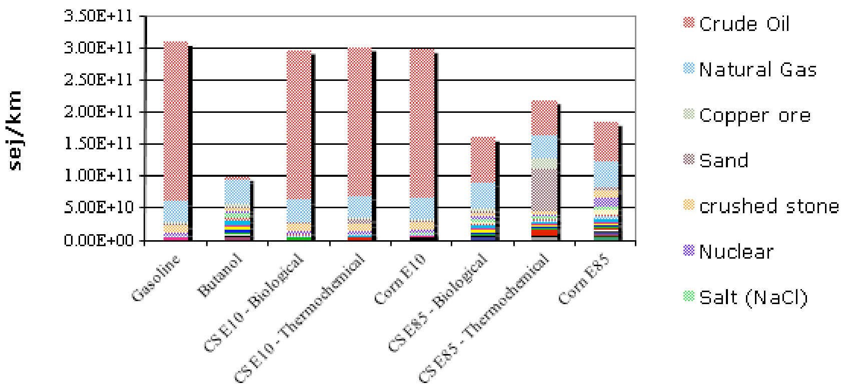

Figure 15: Ecological Cumulative Exergy Consumption for producing gasoline, 100% butanol, 10% ethanol/90% gasoline, and 85% ethanol/15% gasoline. Values are for driving 1 km in a 2012 Ford Fusion flex-fuel vehicle.

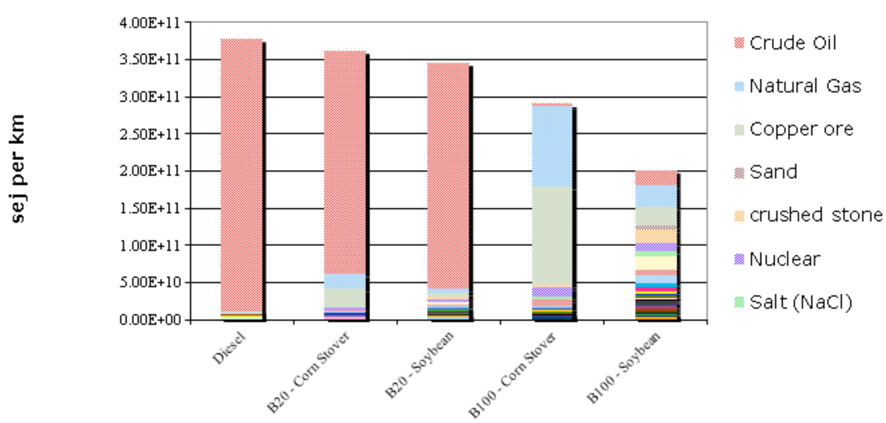

Figure 16: Ecological Cumulative Exergy Consumption for producing diesel, 20% biodiesel/80% diesel, and 100% biodiesel. Values are for driving 1 km in a 2012 Volkswagon Jetta diesel powered vehicle.

6 Comparison with Previous Studies

The reductions in crude oil and fossil fuel requirements for using corn stover ethanol in place of gasoline agree with the values reported in literature. Corn stover ethanol produced by fermentation gave a 91% reduction in crude oil consumption as compared to gasoline on an energy equivalent basis. This matches the crude oil reductions of 88-96% reported by Baral et al. [12] and Sheehan et al. [3]. The overall fossil fuel reduction for this fuel was 76%, which also closely agrees with the 74% reduction in fossil fuel requirements reported by Levelton Engineering Ltd. [13]

The CO_2 emissions discussed in this paper, however, differ greatly from the results of other studies found in literature. Spatari et al. [14] reported that the use of E85 made with corn stover ethanol could reduce CO_2 emissions by 71%, and Ahlgren et al. [17] reported a 94% reduction in greenhouse gas emissions for Fischer-Tropsch diesel made from straw. In this study, E85 made from corn stover ethanol only reduced CO_2 emissions by 6-7%, butanol by 11%, and corn stover biodiesel by 4%. The reason for these large differences lies in the assumptions made. In the studies found in literature, the authors assumed that the amount of CO_2 sequestered during farming the corn stover was equal to the amount of CO_2 emitted during lignin and ethanol combustion. [14, 17] As described in this paper, because it was assumed that the corn stover was agricultural waste, the carbon sequestered during farming was not included and the net CO_2 emissions for all of the corn stover based fuels are much higher as these end use emissions account for approximately 90% of the overall emissions. In addition, for the corn ethanol and soybean biodiesel, which included sequestration during farming, carbon sequestration was estimated using Eco-LCA and the amount of CO_2 sequestered by the farmland was lower than the amount of CO_2 released during fuel combustion.

7 Conclusions

The results of this study suggest that biofuels made from corn stover pose many advantages over gasoline, diesel, corn ethanol, and soybean biodiesel. All of the biofuels studied offer significant reductions in nonrenewable energy use. The fuels made from corn stover, because they are made from agricultural residue and therefore do not require many additional inputs for farming, also have much lower water requirements and reactive nitrogen releases than corn ethanol and soybean biodiesel. Water requirements for producing corn stover butanol, corn stover biodiesel, and corn stover ethanol using the biochemical process are still between 1.4 and 2.4 times as high as for gasoline and diesel, but the water requirement for the thermochemical ethanol production process is actually lower than that for gasoline. Reactive nitrogen losses to the environment are only 3% higher for corn stover butanol and corn stover ethanol produced via fermentation than they are for gasoline. These losses are actually lower for the thermochemically produced ethanol than for gasoline, and they are also lower for corn stover biodiesel than for diesel. Furthermore, while the CO_2 emission reductions found in this study may not be as large as other studies have reported, the results still suggest that the use of biofuels does offer some reduction in CO_2 emissions. Combining all of these benefits with the lower ECEC for the biofuels as compared to their petroleum counterparts, corn stover fuels could be a good option for replacing a portion of the fossil fuels used in transportation.

Corn stover butanol has not been thoroughly studied using LCA before this point. Based on the results of this study, butanol could have larger reductions in fossil fuel consumption, CO_2 emissions, and ECEC than ethanol on a per km basis because it can be used as 100% butanol. Comparing the two fuels on an energy equivalent basis, butanol and ethanol both have their advantages: butanol has slightly lower reactive nitrogen losses, CO_2 emissions, and ECEC, while ethanol requires less water and less corn stover. The thermochemical approach to ethanol production also has its advantages over the biochemical process as water requirements, fossil fuel requirements, CO_2 emissions, and reactive nitrogen losses are all lower, although more corn stover is required and ECEC is high. All of these fuels should be studied further. Corn stover biodiesel also has its advantages, but if natural gas is used to produce the hydrogen required for the process, then this fuel is more fossil fuel dependent than the others and ECEC is much higher.

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Appendices

A Fuel and Feedstock Properties and Assumptions

Table 1: Dry Mass of Corn Stover Required to Produce 514 billion Btu of Fuel

Fuel	kg Dry Corn Stover Before Allocation	kg Dry Corn Stover, Allocated
Ethanol - Biochemical	6.81E+07	6.24E+07
Ethanol - Thermochemical	7.93E+07	7.93E+07
Butanol	8.00E+07	7.30E+07
Biodiesel	9.26E+07	7.93E+07

Table 2: Densities and Lower Heating Values of Fuels

Fuel	Gasoline	Diesel	Ethanol	Butanol	Biodiesel	FT Diesel
Density (kg/gal)	2.819	3.167	2.988	3.065	3.361	3.017
LHV (Btu/gal)	116,090	128,450	76,330	99,837	119,550	123,670

Source: All values came from GREET 2011

Table 3: Fuel Economy and CO_2 Emissions for Different Fuels

Vehicle	Fuel	Fuel Economy (mpg)	Source	CO2 Emissions (g/km)	Source
2012 Ford Fusion	Gasoline	23.0	www.fueleconomy.gov	234	GREET 2011
	E10	22.2	Calculated based on LHV	234	GREET 2011
	E85	16.0	www.fueleconomy.gov	230	GREET 2011
	Butanol	19.8	Calculated based on LHV	222	GREET 2011
2012 Volkswagon Jetta	Diesel	34.0	www.fueleconomy.gov	166	GREET 2011
	B20	33.3	www.fueleconomy.gov	166	GREET 2011
	B100	30.6	www.fueleconomy.gov	161	EPA 2002

B Inputs for Fuel Production Processes

Table 4: Inputs for Producing Corn Stover Ethanol via Fermentation

Inputs	Amount	Units	Source	Cost/unit	Year	2002 Price
Corn stover farming						
Nitrogen as ammonium nitrate	1.89E+06	kg	Spatari et al., 2005	1.94E-01	2000	3.81E+05
Posphorous as P2O5	6.06E+05	kg	Spatari et al., 2005	2.33E-01	2000	1.47E+05
Potash (K) as K2O	1.32E+06	kg	Spatari et al., 2005	1.65E-01	2000	2.27E+05
Diesel (tractor)	4.70E+05	gal	Spatari et al., 2005	5.75E-01	1997	3.03E+05
Diesel (truck)	9.25E+04	gal	Spatari et al., 2005	5.75E-01	1997	5.96E+04
Steel (truck for transport)	5.51E+03	kg	Felix , 2007	2.90E-01	1997	1.79E+03
Cellulosic ethanol production						
Sulfuric acid	2.96E+06	kg	Aden et al., 2002	2.73E-02	2001	8.23E+04
Lime	2.15E+06	kg	Aden et al., 2002	7.66E-02	2001	1.68E+05
Diammonium phosphate	1.47E+05	kg	Aden et al., 2002	1.55E-01	2001	2.32E+04
Corn steep liquor	1.17E+06	kg	Aden et al., 2002	1.77E-01	1998	2.29E+05
Clarifier polymer	2.52E+04	kg	Aden et al., 2002	2.75E+00	2000	7.20E+04
Purchased cellulase	6.14E+06	kg	Aden et al., 2002	1.24E-01	2000	7.89E+05
LPG	8.77E+03	gal	Aden et al., 2002	3.70E-01	1997	3.63E+03
Make-up water	4.43E+07	gal	Aden et al., 2002	1.00E-03	2000	4.61E+04
Cooling water chemicals	4.51E+02	kg	Aden et al., 2002	2.24E+00	2000	1.05E+03
BFW chemicals	2.38E+02	kg	Aden et al., 2002	2.97E+00	2000	7.34E+02
WWT chemicals	7.98E+04	kg	Aden et al., 2002	3.47E-01	2000	2.88E+04
Diesel for transport of chemicals	3.11E+04	gal		5.75E-01	1997	2.00E+04
Pipeline transport (diesel+LPG)	6.02E+05	gal		2.30E-02	2006	1.25E+04
Capital						
Cement	2.02E+04	kg	Felix , 2007	8.40E-02	2004	1.61E+03
Steel (ethanol production)	8.08E+03	kg	Felix , 2007	2.90E-01	1997	2.62E+03
Steel (building)	1.43E+04	kg	Felix , 2007	2.90E-01	1997	4.66E+03
Diesel for cellulosic ethanol transport	5.87E+04	gal	GREET 2008	5.75E-01	1997	3.78E+04

Table 5: Inputs for Producing Corn Stover Ethanol via Gasification

Inputs	Amount	Units	Source	Price	Year	2002 Price
Corn stover farming						
Nitrogen as ammonium nitrate	1.35E+07	kg	Spatari et al., 2005	3.67E+05	2000	3.81E+05
Posphorous as P2O5	4.33E+06	kg	Spatari et al., 2005	1.41E+05	2000	1.47E+05
Potash (K) as K2O	9.45E+06	kg	Spatari et al., 2005	2.18E+05	2000	2.27E+05
Diesel (tractor)	3.36E+06	gal	Spatari et al., 2005	2.70E+05	1997	3.03E+05
Diesel (truck)	6.61E+05	gal	Spatari et al., 2005	5.32E+04	1997	5.96E+04
Steel (truck for transport)	3.94E+04	kg	Felix , 2007	1.60E+03	1997	1.79E+03
Cellulosic ethanol production						
Water	5.01E+07	kg	Mu et al., 2010			1.38E+04
MgO	1.71E+04	kg	Mu et al., 2010	6.89E+03	2002	6.89E+03
Olivine	2.14E+05	kg	Mu et al., 2010	4.08E+04	2002	4.08E+04
Synthesis Catalyst (molybdenite)	1.14E+03	kg	Mu et al., 2010	1.32E+04	2002	1.32E+04
Tar Reforming Catalyst	8.57E+02	kg	Mu et al., 2010	8.82E+03	2002	8.82E+03
Oxidizer	5.23E+04	kg sulfur	Phillips et al., 2007	7.85E+03	2002	7.85E+03
WWT	2.38E+04	kg	Aden et al., 2002	8.27E+03	1997	9.26E+03
Boiling chemicals	7.08E+01	kg	Aden et al., 2002	4.07E+01	1997	4.56E+01
Cooling water chemicals	1.35E+02	kg	Aden et al., 2002	3.10E+00	1997	3.47E+00
Capital						
Cement	2.30E+04	kg		1.93E+03	2004	1.84E+03
Steel (equipment)	9.20E+03	kg		2.67E+03	1997	2.99E+03
Steel (building)	1.63E+04	kg		4.74E+03	1997	5.30E+03
Diesel for ethanol transport	4.43E+07	gal	GREET 2008	4.17E+04	1997	4.67E+04

Table 6: Inputs for Producing Corn Stover Butanol

Inputs	Amount	Units	Source	Price	Year	2002 Price
Corn stover farming						
Nitrogen as ammonium nitrate	1.80E+06	kg	Spatari et al., 2005	4.88E+04	2000	5.08E+04
Posphorous as P2O5	5.76E+05	kg	Spatari et al., 2005	1.88E+04	2000	1.95E+04
Potash (K) as K2O	1.26E+06	kg	Spatari et al., 2005	2.91E+04	2000	3.02E+04
Diesel (tractor)	4.47E+05	gal	Spatari et al., 2005	3.60E+04	1997	4.03E+04
Diesel (truck)	8.80E+04	gal	Spatari et al., 2005	7.08E+03	1997	7.93E+03
Steel (truck for transport)	5.24E+03	kg	Felix , 2007	2.13E+02	1997	2.38E+02
Pretreatment/Hydrolysis						
Sulfuric acid	2.81E+06	kg	Aden et al., 2002	7.67E+04	2001	7.83E+04
Lime	2.05E+06	kg	Aden et al., 2002	1.57E+05	2001	1.60E+05
Diammonium phosphate	1.39E+05	kg	Aden et al., 2002	2.17E+04	2001	2.21E+04
Fermentation and Distillation						
Corn steep liquor	1.12E+06	kg	Aden et al., 2002	1.98E+05	1998	2.17E+05
Enzymes	2.40E+04	kg	Aden et al., 2002	6.59E+04	2000	6.85E+04
Make-up water	4.22E+07	gal	Aden et al., 2002	4.22E+04	2000	4.39E+04
Cooling water chemicals	4.29E+02	kg	Aden et al., 2002	9.64E+02	2000	1.00E+03
BFW chemicals	2.26E+02	kg	Aden et al., 2002	6.71E+02	2000	6.98E+02
WWT chemicals	7.60E+04	kg	Aden et al., 2002	2.64E+04	2000	2.74E+04
clarifier polymer	2.40E+04		Aden et al., 2002	1.38E+04	2000	1.43E+04
Capital						
Cement	9.87E+03	kg		8.29E+02	2004	7.88E+02
Steel (equipment)	3.95E+03	kg		1.14E+03	1997	1.28E+03
Steel (building)	7.01E+03	kg		2.03E+03	1997	2.28E+03
Diesel for Butanol Transport	4.49E+04	gal	GREET 2008	2.58E+04	1997	2.89E+04

Table 7: Inputs for Producing Corn Stover Biodiesel

Inputs	Amount	Units	Source	Price	Year	2002 Price
Corn stover farming						
Nitrogen as ammonium nitrate	8.38E+06	kg	Spatari et al., 2005	2.27E+05	2000	2.37E+05
Posphorous as P2O5	2.69E+06	kg	Spatari et al., 2005	8.76E+04	2000	9.11E+04
Potash (K) as K2O	5.86E+06	kg	Spatari et al., 2005	1.35E+05	2000	1.41E+05
Diesel (tractor)	2.08E+06	gal	Spatari et al., 2005	1.68E+05	1997	1.88E+05
Diesel (truck)	4.10E+05	gal	Spatari et al., 2005	3.30E+04	1997	3.70E+04
Steel (truck for transport)	2.44E+04	kg	Felix , 2007	9.92E+02	1997	1.11E+03
Biodiesel Production						
Electricity	6.79E+06	kWh	Wright et al., 2010	3.07E+05	1997	3.44E+05
Catalyst			Wright et al., 2010	1.33E+05	2007	1.15E+05
Hydrogen	1.21E+06	kg	Wright et al., 2010	1.78E+06	2007	1.55E+06
Capital						
Cement	1.40E+04	kg		1.18E+03	2004	1.12E+03
Steel (equipment)	5.60E+03	kg		1.62E+03	1997	1.82E+03
Steel (building)	9.93E+03	kg		2.88E+03	1997	3.23E+03
Diesel for fuel transport	3.63E+04	gal	GREET 2008	2.08E+04	1997	2.33E+04

Inputs for corn butanol, soybean biodiesel, gasoline, and diesel are not included here but are identical to those found in the supplementary information for the report by Baral and Bakshi. [26]

C Results Tables

Table 8: Fossil Fuel Use, Water Use, and CO_2 Emissions for 514 billion Btu of Fuel

	Crude Oil (MJ)	Natural Gas (MJ)	Coal (MJ)	Water (L)	WTT CO2 (g)
Gasoline	4.49E+08	5.97E+07	1.53E+06	2.92E+08	4.33E+09
Diesel	9.07E+08	1.20E+08	3.05E+06	5.86E+08	8.43E+09
CS Ethanol - Biological	3.98E+07	7.45E+07	6.29E+06	6.83E+08	1.79E+09
CS Ethanol - Thermochemical	2.09E+06	6.76E+07	7.03E+05	1.85E+08	1.58E+09
Corn Ethanol	1.84E+07	7.16E+07	5.75E+06	3.68E+09	2.84E+09
CS Butanol	7.61E+06	6.99E+07	6.66E+06	7.09E+08	1.40E+09
CS Biodiesel	5.84E+06	1.87E+08	1.30E+06	8.01E+08	7.33E+09
Soybean Biodiesel	4.59E+07	7.03E+07	1.39E+07	6.37E+09	-5.05E+09

Table 9: Fossil Fuel Use, Water Use, and CO_2 Emissions for 1 km in a 2012 Ford Fusion

	Crude Oil (MJ)	Natural Gas (MJ)	Coal (MJ)	Water (L)	WTT CO2 (g)	End-Use CO2 (g)
Gasoline	2.74E+00	3.65E-01	9.32E-03	1.78E+00	2.65E+01	1.64E+01
Butanol	4.64E-02	4.27E-01	4.07E-02	4.33E+00	9.45E+00	5.87E+00
CS E10 - Biological	2.57E+00	3.71E-01	1.13E-02	1.94E+00	2.55E+01	1.58E+01
CS E10 - Thermochemical	2.55E+00	3.68E-01	8.98E-03	1.74E+00	2.53E+01	1.57E+01
Corn E10	2.56E+00	3.70E-01	1.11E-02	3.19E+00	2.58E+01	1.61E+01
CS E85 - Biological	7.86E-01	4.44E-01	3.29E-02	3.73E+00	1.53E+01	9.51E+00
CS E85 - Thermochemical	6.01E-01	4.10E-01	5.46E-03	1.29E+00	1.35E+01	8.36E+00
Corn E85	6.81E-01	4.30E-01	3.02E-02	1.84E+01	1.96E+01	1.22E+01

Table 10: Fossil Fuel Use, Water Use, and CO_2 Emissions for 1 km in a 2012 Volkswagon Jetta

	Crude Oil (MJ)	Natural Gas (MJ)	Coal (MJ)	Water (L)	WTT CO2 (g)	End-Use CO2 (g)
Diesel	4.15E+00	5.50E-01	1.39E-02	2.68E+00	3.85E+01	1.66E+02
B20 - Corn Stover	3.39E+00	6.17E-01	1.25E-02	2.90E+00	3.80E+01	1.66E+02
B20 - Soybean	3.43E+00	5.12E-01	2.39E-02	7.91E+00	2.69E+01	1.66E+02
B100 - Corn Stover	2.86E-02	9.15E-01	6.34E-03	3.92E+00	3.58E+01	1.60E+02
B100 - Soybean	2.24E-01	3.44E-01	6.80E-02	3.12E+01	-2.47E+01	1.61E+02

Table 11: Nitrogen Footprint for 514 billion Btu of Fuel

	N Mobilization (g N)	N in End Use Products (g N)	N20 Losses (g N)	Nox Losses (g N)	N Loading to Water (g N)
Gasoline	3.69E+06	1.32E+06	1.56E+05	7.18E+06	3.83E+04
Diesel	7.40E+06	2.64E+06	2.98E+05	1.44E+07	7.66E+04
CS Ethanol - Biological	9.29E+08	1.67E+07	3.72E+06	3.05E+06	8.51E+05
CS Ethanol - Thermochemical	1.11E+09	1.21E+06	4.13E+06	1.94E+06	8.33E+04
Corn Ethanol	1.13E+09	7.47E+07	5.88E+06	7.43E+06	5.47E+06
CS Butanol	1.07E+09	1.38E+07	4.25E+06	2.46E+06	8.76E+05
CS Biodiesel	6.93E+08	3.09E+06	2.70E+06	7.17E+06	1.36E+05
Soybean Biodiesel	8.75E+08	2.03E+08	7.23E+06	9.17E+06	1.34E+07

Table 12: Nitrogen Footprint for 1 km in a 2012 Ford Fusion

	N Mobilization (g N)	N in End Use Products (g N)	N20 Losses (g N)	Nox Losses (g N)	N Loading to Water (g)
Gasoline	2.25E-02	8.07E-03	9.53E-04	4.39E-02	2.34E-04
Butanol	7.18E+00	9.25E-02	2.84E-02	1.66E-02	5.85E-03
CS E10 - Biological	4.43E-01	1.51E-02	2.58E-03	4.23E-02	6.04E-04
CS E10 - Thermochemical	4.81E-01	8.03E-03	2.61E-03	4.17E-02	2.53E-04
Corn E10	4.91E-01	3.86E-02	3.33E-03	4.40E-02	2.49E-03
CS E85 - Biological	4.98E+00	9.14E-02	2.01E-02	2.58E-02	4.61E-03
CS E85 - Thermochemical	5.43E+00	7.69E-03	2.05E-02	1.90E-02	4.59E-04
Corn E85	5.56E+00	3.68E-01	2.90E-02	4.59E-02	2.69E-02

Table 13: Nitrogen Footprint for 1 km in a 2012 Volkswagon Jetta

	N Mobilization (g N)	N in End Use Products (g N)	N20 Losses (g N)	Nox Losses (g N)	N Loading to Water (g)
Diesel	3.38E-02	1.21E-02	1.36E-03	6.58E-02	3.50E-04
B20 - Corn Stover	6.50E-01	1.26E-02	3.53E-03	6.01E-02	4.08E-04
B20 - Soybean	8.13E-01	1.92E-01	7.60E-03	6.19E-02	1.23E-02
B100 - Corn Stover	3.39E+00	1.51E-02	1.32E-02	3.51E-02	6.65E-04
B100 - Soybean	4.28E+00	9.94E-01	3.53E-02	4.48E-02	6.55E-02

Table 14: Total ECEC for 514 billion Btu of Fuel

Fuel	ECEC (sej)
Gasoline	5.06E+19
Diesel	8.30E+19
CS Ethanol - Biological	1.92E+19
CS Ethanol - Thermochemical	3.10E+19
Corn Ethanol	2.41E+19
CS Butanol	1.63E+19
CS Biodiesel	5.96E+19
Soybean Biodiesel	4.27E+19

Table 15: Total ECEC for 1 km in a 2012 Ford Fusion

Fuel	ECEC (sej)
Gasoline	3.09E+11
Butanol	9.97E+10
CS E10 - Biological	2.96E+11
CS E10 - Thermochemical	3.01E+11
Corn E10	2.98E+11
CS E85 - Biological	1.61E+11
CS E85 - Thermochemical	2.19E+11
Corn E85	1.85E+11

Table 16: Total ECEC for 1 km in a 2012 Volkswagon Jetta

Fuel	ECEC (sej)
Diesel	3.79E+11
B20 - Corn Stover	3.63E+11
B20 - Soybean	3.46E+11
B100 - Corn Stover	2.91E+11
B100 - Soybean	2.02E+11

D Calculations

Farming, steel, and cement inputs for the biochemical method of ethanol production were taken from the literature sources listed in Table 4, found in Appendix B. For each of the other corn stover fuels, these inputs were calculated relative to the amounts required for ethanol, as shown in the following equations for the amount of nitrogen fertilizer and the amount of steel required. "Equip" refers to the installed equipment cost and "index" refers to the plant cost index used to account for inflation. The diesel referred to here is used for transport of the final fuel, the gallons of each fuel represent the number of gallons that gives an energy content of 514 Btu, based on the LHV.

$$Nitrogen_{BuOH} = Nitrogen_{EtOH} * \frac{kgCornStover_{BuOH}}{kgCornStover_{EtOH}}$$

$$Steel_{BuOH} = Steel_{EtOH} * \frac{Equip_{BuOH}}{Equip_{EtOH}} * \frac{index_{2002}}{index_{year}}$$

$$Diesel_{BuOH} = Diesel_{EtOH} * \frac{Gallons_{BuOH}}{Gallons_{EtOH}}$$

The results reported in Appendix C were obtained as follows: the quantity of each resource consumed or emitted for the production of one of the inputs was obtained by multiplying the dollar amount for the input by an Eco-LCA coefficient. The Eco-LCA coefficient depends on the economic sector for the input and the resource being studied. A sample equation for calculating ECEC using this method is shown below:

$$ECEC = Price * Coefficient$$

For each of the fuel blends used for the per km comparisons, the number of gallons of fuel required to travel 1 km was calculated based on the fuel economies reported in Table 3, found in Appendix A. Then the equation shown below was used to calculate the results for the fuel blend.

$$ECEC_{E85} = Gallons_{E85} * (0.15 * ECEC_{GallonGasoline} + 0.85 * ECEC_{GallonEtOH})$$